Power flow analysis in a distributed network for a smart grid system

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ABSTRACT

This article presents the implementation of a hybrid renewable energy-based smart grid in a distributed system. Photovoltaic (PV) and wind generation are variable and time-dependent, yet they are very efficient and correlated, making them perfect for a two-source hybrid system. To maximize the generated power, using the maximum power point tracker (MPPT) technique, the incremental conductance (IC) algorithm is employed. The proportional integral (PI)-based MPPT controller is chosen to improve the efficiency of conventional MPPT controllers. A battery system is implemented as an energy management system (EMS) to aid in transferring or managing the high load throughout peak and off-peak hours. The proposed system uses an optimization technique called genetic algorithm (GA) to control the inverter voltage. The GA-tuned PI controller performs efficiently and has less harmonic distortion than the traditional sinusoidal pulse width modulation (SPWM) control method. The designed system uses real-time measurable parameters as inputs and is simulated in Matlabtool. The system generates 42 kW of solar power and 250 kW of wind power; the total harmonic distortion (THD) value is 5% less than the SPWM technique. For future work, flexible alternating current transmission system (FACTS) devices can improve the power quality and lower the oscillations.

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1. INTRODUCTION

Alternative renewable energy systems (RES), like solar and wind energy [1], has attracted energy sectors to create electricity on a massive scale due to benefits such as pollution-free, globally available, and free of charge. As a result, grid integration of RES with all technological consequences is crucial to the long-term development of smart cities [2]. An electric power distribution network comprises a group of energy users who communicate with a utility grid in real time [3]. Solar energy generation is based on converting light energy into electrical energy and depends on the irradiance and temperature across the PV panel. The panel absorbs the photons and converts them into a direct current (DC) electric source [4]. Maximum power point (MPP) tracking (MPPT) is a control approach aimed at extracting full power from a photovoltaic (PV) module by ensuring the operating point characteristic at the maximum achievable output power [5].

This technique uses different algorithms in which ICis employedto address several issues with the perturb and observe (P&O) algorithm. The purpose of IC is to improve energy output and delayed times in a radiation-heavy environment [6]. The wind energy system captures wind energy and transforms it into electrical energy. Its output power changes with wind speed [7]. As a critical component in DC grid connectivity, the DC-DC converter [8] should provide the following features: bidirectional power flow, DC fault blocking, and voltage step-up and step-down levels. The boost converter is implemented in this article, which increases the output voltage from the input voltage. The proposed renewable systems utilize the PI-based MPPT control [9] method for the DC-DC boost converter. Over the last two decades, many pulse width modulation (PWM) control techniques have been developed. In the Sinusoidal pulse width modulation (SPWM) approach, the requisite signals for inverter gates are created by evaluating the reference sine wave with the triangular carrier signal [10].

Metaheuristic algorithms have recently been applied to address complicated real-world engineering, economics, management, and political issues. Genetic algorithm (GA) is an inspiration for the evolution process in biology and is an established metaheuristic algorithm [11]. The Chromosomes are termed solution space points and are handled by frequently changing their population via genetic operators. Selection, mutation, and crossover are biologically inspired operators [12]. Due to the stochastic nature of solar and wind power and the abrupt fluctuations in power provided by variable renewables, storage systems are vital. The energy management system (EMS) [13] is a comprehensive control system that handles energy flows between power sources, loads and the utility grid efficiently and flexibly. A smart meter [14] is a more advanced energy meter that can monitor a household's energy use and send further information to the utility supplier. Smart meters can read real-time energy usage data, including voltage and current level, phase angle and frequency, and securely transmits that data [15]. The smart grid transforms the present conventional grid into an updated grid capable of cooperating and responding. Generators, users and consumers might be intelligently connected to the grid to deliver efficient, secure, and cost-effective supplies [16]. RES provide the majority of their energy at specific times of the day [17]. Its power generation does not correspond to peak demand hours. Wind and solar energy are unpredictable [18], [19]. This paper presents the proposed smart grid system's implementation by hybrid renewable resources and a battery system.

2. METHODS

This section goes through each component of the proposed model. The system consists of two solar PV panels, a battery system, a wind energy conversion system, and a grid-connected distribution network. The RES's three-phase output is combined and linked to non-linear loads and the grid utilizing transmission lines. The filter circuit connects the load and the inverter to decrease harmonics. A hybrid power system may comprise a wind turbine, a PV array, and a storage device such as a battery. That might all be a part of a hybrid energy system. Individual component modeling is the initial step in properly selecting subsystems and components for optimal configuration size. In addition to the regular grid's generating facilities and transmission network, the smart grid contains smart control and measuring equipment. Data on power consumption, availability from different sources, grid transmission capacity, and power flow throughout the system may be gathered by a wide variety of computer-controlled generators along with additional power sources, meters, displays, and smart electronic devices. Software programs designed for the grid help in calculating power efficiency while maintaining track on what customers and producers are up to in terms of electricity use. In this model, the output power is evaluated in:

$$E_{PV}(t) = G(t) * A * \eta_{PV} \tag{1}$$

$$\eta_{pv} = \eta_{pc}\eta_r \,[1 - \beta(-T_{c-ref} + T_C] \tag{2}$$

$$T_c = \left(\frac{NT-20}{800}\right) G(t) + T_a \tag{3}$$

where, η_{PV} is the generation of PV, G(t) is solar irradiations (W/m2), A is PV generation area (m2), η_{PC} is the efficiency of power conditioning, $\eta_C$is the efficiency of reference module, β is temperature coefficient, T_{c-ref} is reference temperature (°C), $T_a$is the ambient temperature (°C), NT is the temperature of the nominal operating cell. The complexities of modeling are reflected in its correct performance forecast; nevertheless, designing a flawless model is either overly complicated or highly time-demanding. Solar irradiation and ambient temperature determine a PV array's power production. Figure 1 depicts the suggested model's block diagram. The expressions are illustrated in:

$$E_{PV}(t) = E_{PV,L}(t) + E_{PV,B}(t) \tag{4}$$

$$E_{WE}(t) = E_{WE,L}(t) \tag{5}$$

2.1. Modelling of solar PV system

Solar PV systems are considered RES in this article. A standard solar cell design may be represented by an optimal source of current, internal shunt resistance and series resistance, and a diode representing the p-n semiconductor junction [20]. From the semiconductor theory, the basic equation which explains the I-V properties of a solar cell is provided in (6). The solar cell current's general expression and light generated currentare in (7) and (8) respectively.

$$I = I_L - I_o\left[\left(\frac{qV}{akT}\right) exp - 1\right] \tag{6}$$

$$I = I_L - I_a\left[\exp\left(\frac{V+R_s I}{V_t a}\right) - 1\right] - \left(\frac{V+R_s i}{R_{sh}}\right) \tag{7}$$

$$I_L = (I_{L.n} + \Delta_T K_I)\frac{G}{G_n} \tag{8}$$

Where, I_L is the solar array's PV current,$I_L = I_{L.cell}N_P$ and I_o is the solar array's PV current, $I_0 = I_{o.cell}N_P$, $V_t$is the array's thermal voltage, R_{sh} is parallel resistance,R_s is equivalent resistance in series, and a is arbitrarily chosen. The light generated current is $I_{L.n}$ Δ_T the nominal and actual temperature's difference, G is surface irradiation and $G_n$nominal irradiance. The temperature dependency of the diode saturation currentI_o may be represented as (9). $I_{sc,n}$ and$V_{oc,n}$ are short circuit current and open circuit voltage at nominal temperature. The PV array converts solar energy into DC power, coupled to the DC bus via a DC/DC boost converter. However, due to non-linear PV panel properties and stochastic changes in solar irradiation, an MPP is always accessible for any given operational state of a PV array [21].

$$I = \left[\frac{I_{sc,n}}{\left(\left(\frac{V_{oc,n}}{aV_{t,n}} - 1\right) - 1\right) exp}\right] \tag{9}$$

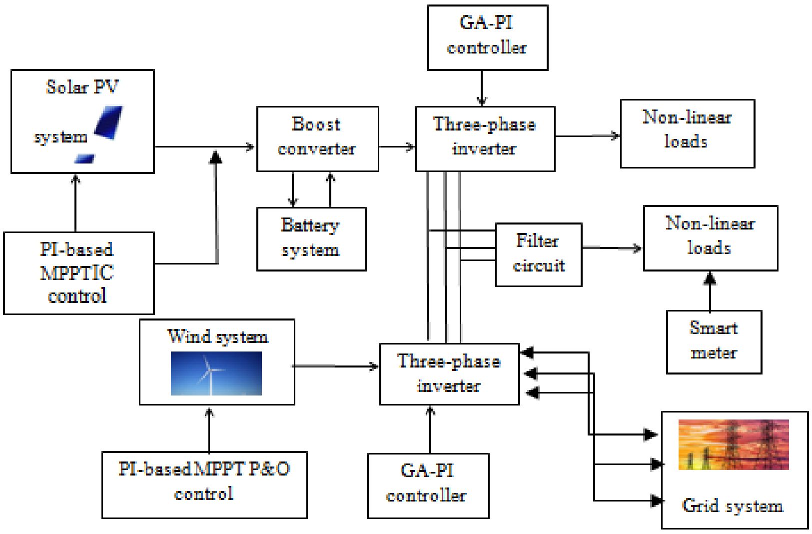


Figure 1. Proposed block diagram of the smart grid system

2.2. Wind energy system model

The wind generator [22] comprises a wind turbine and a permanent magnet synchronous generator (PMSG). The diode rectifier transfers the three-phase alternating current (AC) voltage into a DC source voltage. The boost converter is employed, whose voltage the MPPT controller's PWM signal adjusts the input-output ratio. To determine the PWM signal, the MPPT controller analyzes the voltage and current of the wind generator output. The kinetic energy of an object moving and the mass is denoted as (10). Hence P_w is represented as in (11) and as a result, the actual power collected by the wind turbine is denoted in (12). The wind turbine torque may be stated as in (13).

$$e_k = \frac{1}{2}mv^2 , m = (Ad)\rho \quad (10)$$

$$P_w = \frac{e_k}{t} = \frac{\frac{1}{2}\rho \, Adv^2}{t} = \frac{1}{2}\rho Av^3 \quad (11)$$

$$P_{WT} = \frac{C_P(\lambda,\beta)\rho \, Av^3}{2} \quad (12)$$

$$T_{WT} = \frac{C_{t(\lambda,\beta)\rho \, ARv^2}}{2} \quad (13)$$

d is the traveled distance of the wind, ρ air density, and A is the rotor blade swept area. The kinetic energy over time (t) is the wind turbine's mechanical energy (P_w). Where R is the radius of the turbine, the rotor speed and power collected by the wind turbine would fluctuate as the wind speed varies. The maximum power is attained from different rotor speeds, so the MPPT controller is utilized to extract the maximum output. Energy charged by the battery is represented in (14) and (15) represents the energy supply from the battery to the load. Where $\eta_C$the efficiency capacity of the battery is, η_{disc} is the efficiency of discharge capacity. Finally, the (16) illustrates the total energy from the whole system.

$$E_{B,In}(t) = \eta_C * \eta_{disc} * [E_{PV,B}(t)] \quad (14)$$

$$E_{B,L}(t) = \eta_{disc} * [E_{B,In}(t)] \quad (15)$$

$$E_L(t) = [E_{WE,L}(t) + \eta_{inv} * (E_{PV,L}(t) + E_{B,L}(t)] \quad (16)$$

2.3. Boost converter working principle

The boost converter increases the output voltage from the input. Due to the switches in this circuit, it may operate in two modes [23]. In the closed state, the energy is stored in the inductor while the capacitor releases it. The capacitor stores the energy whenever the switch is turned on, and the inductor releases it. Because the inductor, capacitor, switch, and diode does not consume energy in ideal conditions, two basic conservation rules must exist between the output and the input. The first law is the law of energy balance in (17) that states that the energy input must equal the output energy.

$$P_i = P_o, V_i I_i = I_o V_o \quad (17)$$

The second law in (18) is the balance of charge, which states that the input charge equals the output charge. The current on the input side could only deliver charge to the output side while the switch is open, and the duration is (1-d) T in one T-period. Using the equation, we may obtain the primary connection between the input and output voltage (19). Where d is the duty cycle and is a positive number smaller than one, hence is V_o greater than the value of V_i. The equation can fix the input voltage, solar PV and battery's frequency, output power, and output voltage (20)-(22). Where the $E_{PV,inv}(t)$, $E_{WE,inv}(t)$ are the energy output from wind and solar energy, respectively, and η_{inv} is the inverter's efficiency.

$$I_i(1-d)T = I_o T \quad (18)$$

$$V_o = \frac{V_i}{1-d} \quad (19)$$

$$E_{PV,inv}(t) = E_{PV}(t) * \eta_{inv} \quad (20)$$

$$E_{WE,inv}(t) = E_{WE}(t) * \eta_{inv} \quad (21)$$

$$E_{B,inv}(t) = [(E_B(t-1) - E_L(t)/\eta_{inv} * \eta_{disc}] \quad (22)$$

2.4. MPPT control techniques

The P&O strategy is the most commonly used in MPPT controllers. The PI-based MPPT controller [24] gives higher efficiency to the converter output. In the wind system, this approach depends on gradually changing the rotor speed and noting the variations in power. Thus, changing the generator's output voltage will cause the rotor speed to change. Changing the voltage might be accomplished by modifying the boost converter's duty cycle. If increasing the duty cycle increases power, the orientation of the perturbation signal remains the same as the preceding cycle. If, on the other hand, the perturbation signal results in a drop in power, the direction of the perturbation signal is the reverse of the previous cycle. According to (23) represents the power change and defines the P&O algorithm [25] approach.

$$\Delta P = P(n) - P(n-1) \tag{23}$$

To evaluate the effect of a voltage change, the controller in the suggested solar PV system keep monitors on small changes in the current and voltage of the PV array using the IC technique. This method requires more processing power from the controller and so is slower than the P&O algorithm when it comes to detecting shifting circumstances. The IC technique finds the maximum power point by comparing the IC ($\Delta I/\Delta V$) to the array conductance. The voltage output is the MPP voltage, while these two are equal ($I/V= \Delta I/\Delta V$). Up till the irradiance changes and the procedure is repeated, the controller keeps the voltage constant. The closed loop MPPT PI controller block diagram for the PV system is shown in Figure 2.

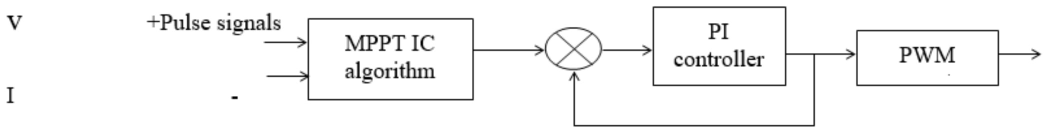


Figure 2. Closed loop diagram of MPPT PI controller in solar PV system

2.5. SPWM control technique

PWM control techniques are one approach for improving the distortion-free zone in high-power converters. SPWM switching [26] is simple to develop in analog and digital circuits. Compared to the reference signal, the carrier signal frequency is quite high. The modulation index is the ratio of the reference signal to the carrier signal amplitude. The frequency of the reference signal defines the frequency of the inverter output, while the amplitude of the reference signal regulates the modulation index and, therefore, the root mean square (RMS) output voltage. SPWM has more harmonic distortion than conventional switching methods, particularly at high modulating indexes. SPWM has large switching losses as well. SPWM is the simplest to learn but cannot fully utilize the DC bus voltage. The SPWM control technique is shown in Figure 3.

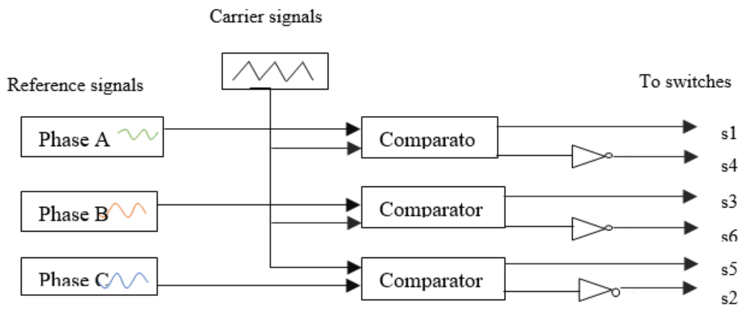


Figure 3. SPWM control technique

2.6. Genetic algorithm

GAs are a stochastic big search approach replicating the natural evolution process and is one of the optimization approaches. As computer systems improve, GA becomes more valuable for optimization [27]. The GA begins with no knowledge of the proper solution to arrive at the optimal answer. It relies entirely on reactions from its surroundings and evolutionary operators like reproduction, crossover, and mutation. GA begins with a single chromosome and evaluates its fitness value. The flowchart of GA is shown in Figure 4.

The fittest chromosomes were chosen as parents, replicated, crossed, and modified. The fitness value of the offspring is determined and based on the value, either picked or ignored from the population. A generation is a name given to each repetition of this procedure. GA is commonly iterated for 0 to 500 generations or more. A run is a collection of generations. After a run, the population frequently contains one or more providing the best value chromosomes. Because unpredictability is crucial in every run, two runs with various random number seeds will often generate distinct detailed behaviors. GA researchers frequently present numbers averaged over several runs of the GA with the same subject.

2.6.1. GA-based PI tuning method

As that is an indirect control action, a PI controller is used. Every control parameter is represented as a chromosomal binary string [28]. The PI controller gains are tuned using a GA. The chromosomal binary strings Kp and Ki, are used to encode the parameters Kpand Ki. The mathematical equation of the PI controller is given (24).

$$u(t) = e(t)K_P + K_i \int_0^t e(t)dt \quad (24)$$

Here K_P &K_i are the proportional, integralgain and e(t) are the error signals between the reference and the process value. To create a mating pool, a set of chromosomes is subjected to selection. The primary cause for establishing a mating pool in the GA is to choose healthy adults for reproduction. In our scenario, the parents are selected using proportional fitness selection, which allocates fitness to a reasonable approach in a population with the chance of choosing each chromosome. Higher fitness solutions are much less likely to be removed. It starts with a healthy first generation. The maximum no of iterations of the proposed system is 300.

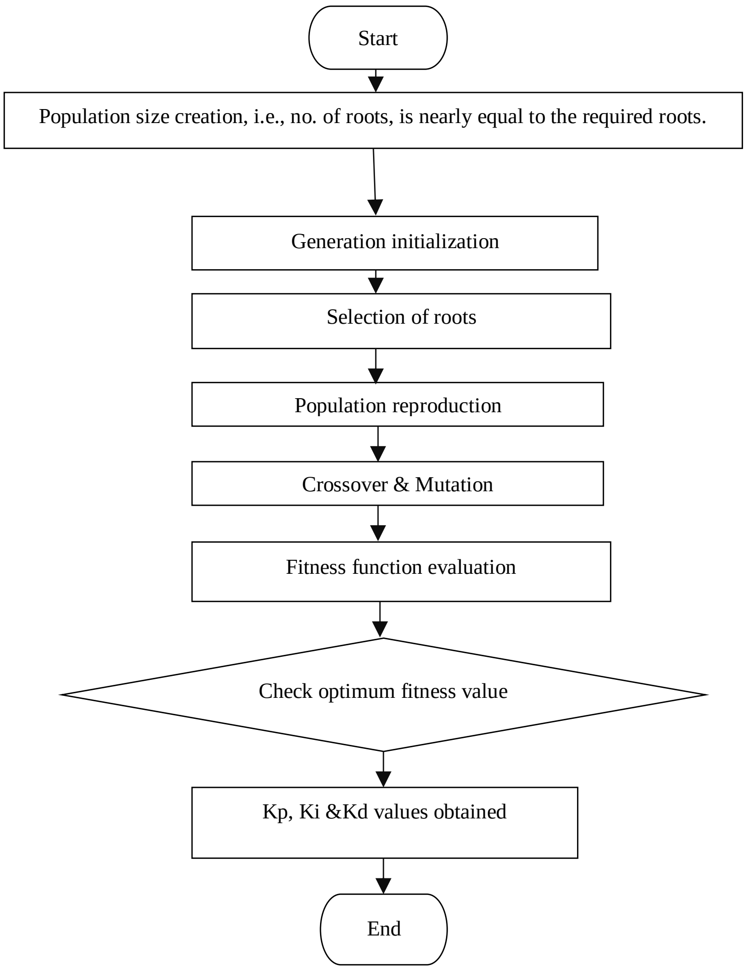


Figure 4. Flowchart of GA

3. RESULTS AND DISCUSSION

The proposed smart grid in a distributed network is simulated in the MATLAB tool. The results are evaluated via scope block. The solar and wind energy generation is based on real-time for 24 hours and the sampling time is 24 sec. The block diagram is displayed in Figure 5.

The first PV panel output voltage and current are 130 V and 240 A. The type of module used in this simulation and its specifications are mentioned in Table 1. The PV voltage is increased using a DC-DC boost converter with an MPPT PI control technique of the IC method. The DC bus voltage is 140 V, and the boost output current is 160 A. Figure 6 shows the converter output voltage and current.

The proposed model uses two panels; the specifications and output of the second PV panel are the same as the first. The total power of the two panels is 42 kW. The battery and nominal voltage are 12 V. The initial state of charge (SOC) is set at 90% of the rated capacity 300 Ah. The wind energy system generates 4 kW AC output voltage. A rectifier is placed for AC-DC conversion. The MPPT PI controller is added to the boost converter for voltage gain. The generated output power of the first solar panel is 21 kW, shown in Figure 7. The DC bus voltage of the wind system is 1015 V, and the wind output power is 250 kW, displayed in Figure 8.

The two renewable energy DC outputs are converted to AC via a three-phase VSI and integrated. The GA-tuned Kp& Ki values are 208.86 and 420.5, respectively. Figure 9 represents the AC output voltage and current. The voltage and current supplied to the grid is 120 V and 10 A respectivelywhich is compared with two techniques, SPWM and GA-PI control. The Figures 9(a) show the grid side AC voltage and current using SPWM technique and Figure 9(b) represents the grid side voltage and current using GA-PI control technique.

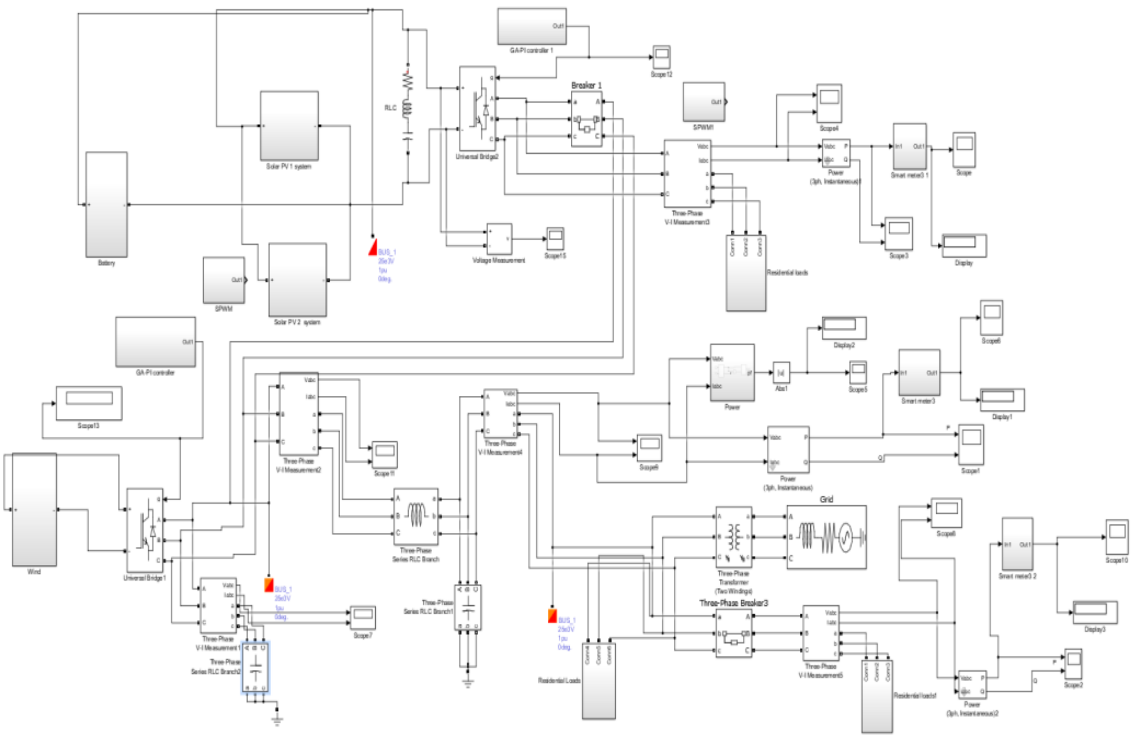


Figure 5. Proposed simulation model of smart grid

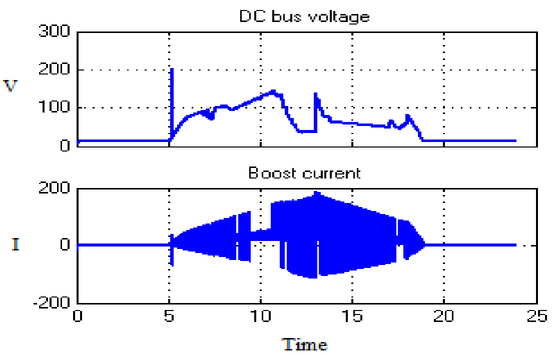


Figure 6. DC bus voltage and current of the converter

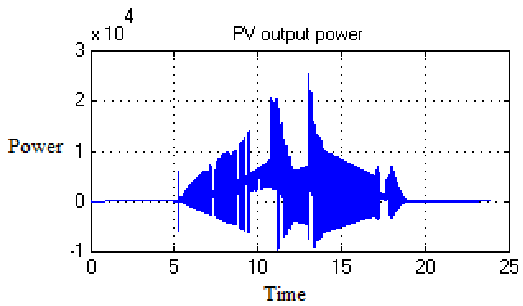


Figure 7. PV power of the first solar panel

Table 1. Specifications of SunPower SPR-305-WHT module

Parameters	Value
Modules connected in series	60
No. of parallel strings	45
Open circuit voltage (Voc)	64.2V
Short circuit current (Isc)	5.96A
MPP voltage	54.7V
MPP current	5.58A

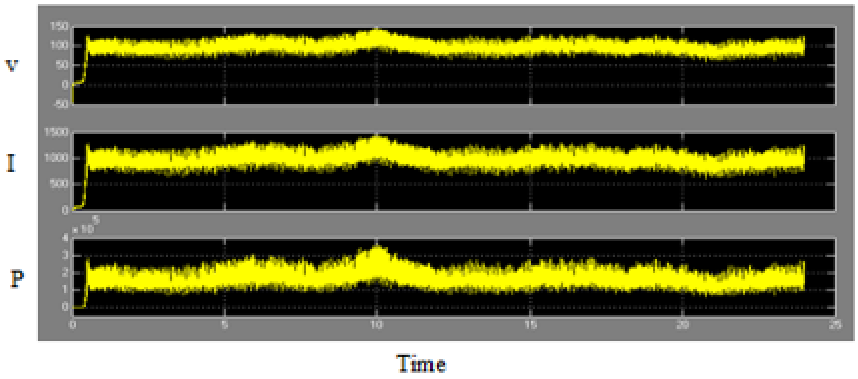
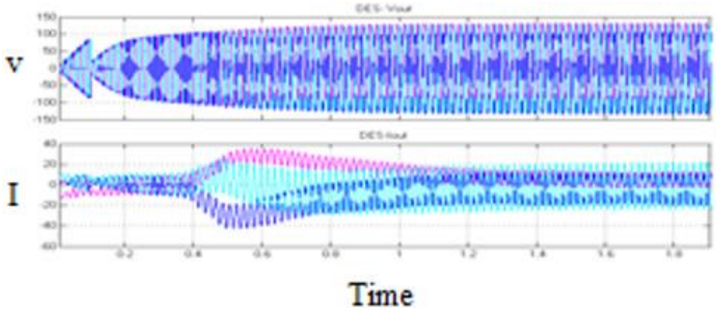
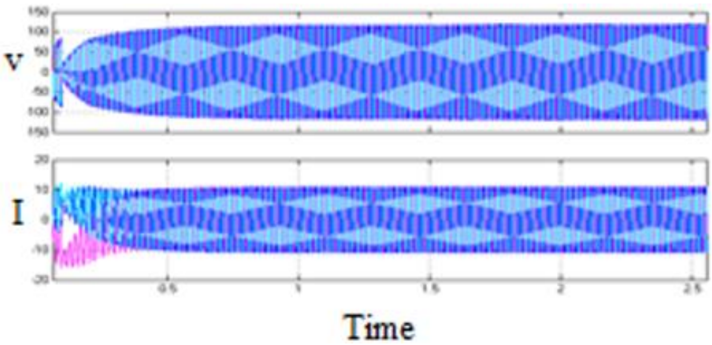


Figure 8. DC bus voltage, current, and power of wind system



(a)



(b)

Figure 9. Inverter output of the proposed system, (a) grid side AC voltage and current using SPWM control and (b) grid side AC voltage and current using GA-PI control

3.1. Comparison between the conventional and proposed method

3.1.1. MPPT technique

The IC technique solves the disadvantages of the P&O method. This method always updates the array terminal voltage based on the MPP voltage [29]. It is based on the incremental and instantaneous conductance of the PV module. Because the change in power is thought to be the result of the array terminal voltage being perturbed, the P&O algorithm is unable to compare the array terminal voltage to the true MPP value. The

MPPT method, which improves on the previous method, is based on a PI controller that attempts to reduce the error between photovoltaic and MPPT block current. PI controllers are generally utilized in most systems because to their ease of use, the convenience of design, low cost, and maintenance simplicity.

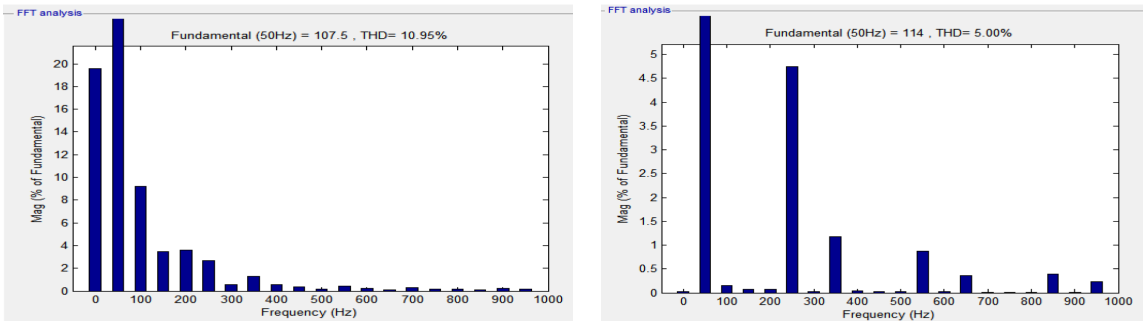
3.1.2. SPWM and GA-PI control method

SPWM is the most basic modulation method used in inverters. However, drawbacks include a relatively narrow linear range and a significant [30]. The proposed system employs a PI controller based on a GA to address this issue. It is an optimization approach, and when compared to standard PWM techniques, the GA-PI tuned controller has much less harmonic distortion and distributed harmonic energy, resulting in less loss, reduced acoustic noise, a smaller filter size, and optimized efficiency. Table 2 presents the comparative analysis of the conventional SPWM and GA-PID controllers.

Table 2. Comparative analysis of conventional and GA-PI controllers

Control technique	Voltage THD	Current THD	Response time	Robustness to load variations
SPWM control	10.96%	11.3 %	95 ms	Poor
GA-PI control	5%	5.2%	15 ms	Good

Figure 10 shows the THD values of the inverter output voltage. From the results, the AC output waveform is sinusoidal and less distorted in the GA-PI technique than in the SPWM method. The THD value of the proposed method is 5% less than the conventional one. Figure 10(a) shows the THD analysis of inverter output voltage using SPWM method. Figure 10(b) shows the THD analysis of inverter output voltage using GA-PI method.



(a) (b)

Figure 10. THD analysis of the inverter output, (a) THD of inverter output using SPWM method and (b) THD of inverter output using GA-PI method

4. CONCLUSIONS

The implementation of a smart grid in a distributed system is developed in this study using the MATLAB/Simulink platform. Renewable wind and solar energy are used as system sources, and both are incorporated into an alternating current source. The combined output of two PV panels is 42 kW, whereas wind power is 250 kW. Power converters are utilised to convert DC to AC and vice versa. In both renewable energy systems, the MPPT approach is employed to achieve MPP. For PV systems, an MPPT-based PI controller based on the IC is developed, which is more efficient than the usual MPPT technique. Traditional SPWM and recommended GA-PI control approaches were evaluated to control the three-phase VSI. The outcomes of both methods are compared, and the GA-based tuning of the PI controller outperforms the SPWM technique in terms of harmonic distortion. The suggested system has a THD of 5%. FACTS devices are integrated in the design to increase power quality and performance in future works.

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